

The emerging state of open clusters upon their violent relaxation

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ABSTRACT

The state after virialization of a small-to-intermediate N -body system depends on its initial conditions; in particular, systems that are, initially, dynamically “cool” (virial ratios $Q = 2T/|\Omega|$ below ~ 0.3) relax violently in few crossing times. This leads to a metastable system (virial ratio $\simeq 1$) which carries a clear signature of mass segregation much before the gentle 2–body relaxation time scale. This result is obtained by a set of high precision N -body simulations of isolated clusters composed of stars of two different masses (in the ratio $m_h/m_l = 2$), and is confirmed also in presence of a massive central object (simulating a black hole of stellar size). We point out that this (quick) mass segregation occurs in two phases: the first one shows up in clumps originated by sub-fragmentation before the deep overall collapse; this segregation is erased during the deep collapse to re-emerge, abruptly, during the second phase that occurs after the first bounce of the system. This way to segregate masses, actual result of a violent relaxation, is an interesting feature also on the astronomical-observational side. In those stellar systems that start their dynamical evolution from cool conditions, this kind of mass segregation adds to the sequent, slow, secular segregation as induced by 2- and 3- body encounters.

Key words: Galaxy: open clusters and associations: general - galaxies: star clusters: general

1 INTRODUCTION

Astronomical observations indicate that several stellar systems (from young and very young open star clusters to rich clusters of galaxies) show a certain degree of segregation of the most luminous and massive components in their inner regions (Bontemps et al. (2010), Kirk et al. (2014), Er et al. (2013), Gouliermis et al. (2006), Raboud & Mermilliod (1998), Raboud (1999), Littlefair et al. (2003)). For instance, the Orion Nebula Cluster (ONC) is mass segregated down to about $5 M_\odot$ despite its young age, estimated to be less than 2 Myr (Hillenbrand & Hartmann (1998), Allison et al. (2009)). The dominant cause of the rapid mass segregation process, for such systems, is still under debate. A dynamical origin is commonly excluded; in fact, many of the systems which show a mass segregation are much younger than their two-body relaxation time, which is usually considered as the time needed to segregate masses. Specifically, the relaxation time is defined as

$$t_{rel} \equiv \frac{v^2}{D[(\Delta v_{\parallel}^2)]} \quad (1)$$

where v is the typical velocity of a star in the system, and $D[(\Delta v_{\parallel}^2)]$ is one of the three, independent, diffusion coefficients

which derive from the Fokker-Planck equation. For simplicity, if we assume that the velocity distribution of the field stars is Maxwellian, with dispersion σ , it is possible to obtain an explicit expression for $D[(\Delta v_{\parallel}^2)]$ and Eq. 1 becomes

$$t_{rel} = \frac{v^2 \sigma X}{4\sqrt{2}\pi G^2 \bar{\rho} \bar{m} \ln \Lambda G(X)} \quad (2)$$

where $\bar{\rho}$ is the mean mass density of the field (target) stars, \bar{m} is the mean mass, $\ln \Lambda$ is the usual Coulomb logarithm, $X \equiv v/(\sqrt{2}\sigma)$ and $G(X)$ is the function

$$G(X) = \frac{1}{2X^2} \left[\operatorname{erf}(X) - \frac{2}{\sqrt{\pi}} X e^{-X^2} \right]. \quad (3)$$

Equation (2) is valid whether the initial conditions are, indeed, not too far from virial equilibrium (see for example Binney & Tremaine (2008)). This is not always a correct assumption, especially if we refer to the study of the early dynamical evolution of stellar systems whose stars form in sub-structured, clumpy regions in sub-virial conditions (De Marchi et al. (2013), Schmeja & Klessen (2006), Adams et al. (2006)). It has been already shown (Farouki & Salpeter (1982), Allison et al. (2009), McMillan et al. (2007)), through N -body simulations, that, if the initial state of a stellar system is out of equilibrium and the initial spatial distribution of its stars is not homogeneous, a significant degree of mass segregation can emerge on very short time-scales, signifi-

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cantly shorter than the two-body relaxation time. Allison et al. (2009) argue that the main mechanism that leads to mass segregation on a short time is related to the short interval of time in which the violent collapse creates a very dense core; typically, it contains about half the mass of the stellar system in a radius of about one tenth of its initial size. They show that the time to segregate masses down to $4 - 5 M_{\odot}$, in the dense core, is comparable to its living time (approximately 0.1 Myr). This is enough to justify also the degree of mass segregation observed in some astrophysical systems, such as the cited ONC (Allison et al. (2009)). On the other hand, Bonnell & Davies (1998) excluded that the observed mass segregation in young stellar clusters could be due to a violent dynamical evolution, introducing, rather, the hypothesis of an in situ formation of the most massive and luminous stars. In their work, they investigated the dynamical evolution of both spherical stellar systems, initially in virial equilibrium, and non-spherical stellar systems in sub-virial conditions. They found that the time-scale for mass segregation was largely unaffected by differences in the initial phase-space distribution of the stars.

A recent paper by Caputo et al. (2014) investigated the role of initial sub-virial conditions on the final state of a set of stellar system on a range of N from 2,048 to 131,072 and intermediate mass black hole therein and found, by a matching of results with some observational data, that the initial values of the virial ratio $Q = 2T/|\Omega|$ should be in the range 0.36-0.50. They also found an enhanced mass segregation in initially cooler systems but they give no evidence of sub-clustering before the collapse.

In the light of the described scenario, it is clear that it is difficult to discriminate between the two formulated interpretations to explain the phenomenon of the rapid mass segregation in young star clusters. Moreover, an additional problem comes from the observational side, because very young star clusters, still sites of star formation processes, are very arduous to observe because they are embedded in high density gas clouds. Therefore, it is hard to prove if the most massive stars form, indeed, very close to the innermost regions or, on the contrary, they form on a large spatial scale and segregate later.

Another dynamical mechanism, not deeply investigated yet (even if already highlighted by Aarseth et al. (1988), McMillan et al. (2012)) and that might play an important role in segregating masses, is the initial rapid fragmentation of a stellar systems whose stars are initially distributed homogeneously with very small initial velocities. McMillan et al. (2007) and McMillan et al. (2012) stressed that several sub-systems form during the collapse phase; in particular, they show, just before the bounce of the system, a certain degree of mass segregation which is preserved after the sequent collapse and rebound. It is important to stress that this kind of segregation occurs before the formation of the short-living core described in Allison et al. (2009).

In this context, we are forced to conclude that the theoretical scenario is still unclear and deserves investigation. Moreover, the real situation is made even more complicated by the presence of a certain number of primordial binaries and/or of black holes, and/or of a background gas (not considered in N -body simulations, so far). In particular, in this paper we study the effects of the violent collapse of an N -body self-gravitating system starting from initial conditions corresponding to a virial ratio $0 \leq Q \leq 1$ with stars uniformly distributed in space. We also check the role played by the presence of both a residual gas after star formation and of a stellar mass black hole on mass segregation and on the stars' velocity dispersion.

In all our N -body simulations, privileging the clarity of re-

sults respect to their generality, we consider the simple case of a bimodal mass spectrum with bodies initially distributed randomly in a sphere of unitary initial radius R .

The organization of the paper is: in Sect. 2 we describe the models of stellar systems we adopted and give a description of both the software and hardware resources used to follow their dynamical evolution; in Sect. 3 we present and discuss the results with attention to both the physics of violently relaxing, intermediate N , systems and to the possible comparison with observational data of real clusters. Finally, in Sect. 4 we list our conclusions and outline the developments needed to get a better insight into the evolution of open clusters emerging from their mother proto-clouds.

2 MODEL

2.1 Stellar systems

We performed a large set of direct N -body simulations of young star clusters with $128 \leq N \leq 1,024$. We adopted a bimodal mass spectrum: “light” stars (each with mass m_l and total number N_l) and “heavy” stars (each with mass m_h and total number N_h) such that $m_h = 2m_l$ and $N_h = N_l$. The initial spatial coordinates of bodies have been sampled from a uniform distribution in a sphere of radius $R = 1$. The initial velocities have random orientations and, in order to determine their absolute values, we assume a certain value of the initial virial ratio Q , defined as

$$Q = \frac{2T}{|\Omega|} \quad (4)$$

where T is the kinetic energy and Ω the potential energy of the N -body system. We vary Q from $Q = 0$, corresponding to the most violent (cold) collapse, up to $Q = 1$, which means virial equilibrium, at steps of 0.1. Small values of Q (“cool” systems) seem to be suggested by observations of young stellar systems where stars appear to be clustered in sub-virial conditions (see, for example, Adams et al. (2006) and Hillenbrand & Hartmann (1998)). We also investigated the gravitational role of a residual gas, modelled as an analytical contribution to the accelerations of stars. This field is represented, at any time t , by a time varying Plummer potential (Plummer (1911))

$$\Phi_P(r; t) = -\frac{GM_G}{\sqrt{r^2 + r_c^2(t)}} \quad (5)$$

where $r_c(t)$ is the core radius, assumed time-dependent, and M_G is the total (constant) gas mass. Another ingredient of our simulations is the inclusion of a particle with a mass significantly larger than the others. This object may be considered as a stellar black hole, whose mass is indicated as m_{BH} . The black hole mass was assumed to be $m_{BH} = 25m_h = 50m_l$. The total mass of the star cluster system, M_C , is assumed as unit of mass, that is

$$M_C = N_h m_h + N_l m_l + M_G + m_{BH} = M_* + M_G = 1 \quad (6)$$

where M_* refers to the total mass in stars. The mass of the gas the stellar system is embedded in is given by assuming a value for the star formation efficiency parameter, that is

$$\mathcal{S} = \frac{M_*}{M_C} = \frac{M_*}{M_G + M_*}. \quad (7)$$

Once given \mathcal{S} , the stellar mass of the cluster is $M_* = \mathcal{S}M_C$ and $M_G = M_C(1 - \mathcal{S})$. We considered two values of \mathcal{S} , $\mathcal{S} = 0.3$ and $\mathcal{S} = 1$ (no gas). Because we are interested in the emerging state

of young open clusters, we evolved our stellar systems up to a relatively short time ($< 5\text{Myr}$), therefore we neglected, in a first approximation, the effects of stellar evolution. For each set of values of the free parameters we performed 30 runs ($\gtrsim 5,000$ simulations, in total) to give a statistical significance to our results.

The results of our simulations will be presented using the crossing time of the system as time unit, that means for the gravitational constant the value $G = 1$. The velocity units are obtained consequently.

2.2 The N -body code

For the purposes of this paper, we used our highly parallel N -body code `HiGPUs` (Capuzzo-Dolcetta et al. (2013)) running on our private machine containing a Central Processing Unit (CPU) Intel i7 950 and 2 nVIDIA Tesla C2050 (Fermi) Graphics Processing Units (GPUs). Although the GPUs used are not the best in terms of cost and computing capability, being old generation cards, thanks to the high single core working frequency they perform well in regime of weak load, i.e. using a number of particles $\lesssim 1,024$ (Capuzzo-Dolcetta & Spera 2013). `HiGPUs` is based on a Hermite 6th order integration scheme (Nitadori & Makino 2008) parallelized using CUDA (or OpenCL) plus OpenMP and MPI to guarantee maximum performance when a hybrid (CPUs+GPUs) computer is used. The integration algorithm is implemented using the technique of block time steps (Aarseth 2003) where the particle time steps are determined using the following formula:

$$\Delta t_i = \frac{1}{\alpha_1 + \alpha_2} \left[\alpha_1 \eta_4 \left(\frac{A_i^{(1)}}{A_i^{(2)}} \right) + \alpha_2 \eta_6 \left(\frac{A_i^{(1)}}{A_i^{(4)}} \right)^{1/3} \right], \quad (8)$$

where

$$A_i^{(s)} \equiv \sqrt{|\mathbf{a}_i^{(s-1)}| |\mathbf{a}_i^{(s+1)}| + |\mathbf{a}_i^{(s)}|^2} \quad (9)$$

and $a_i^{(s)}$ is the s -th time derivative of the acceleration of the i -th particle. Equation 8 represents a weighted mean (with coefficients α_1 and α_2) between the Aarseth criterion for the 4th order Hermite integrator (with accuracy parameter η_4) (Aarseth (2003)) and the generalized Aarseth criterion for the 6th order scheme (with accuracy parameter η_6) (Nitadori & Makino (2008)). The combination with $\alpha_1 = \alpha_2 = \frac{1}{2}$ has been found to be more stable, for the 6th order method, than the two criteria used independently, providing a better total energy conservation and avoiding time steps either too large or too small.

3 RESULTS

Because no significant differences were found when changing the number of stars in the range studied ($128 \leq N \leq 1,024$), in the following we will discuss the results only for $N = 1,024$ that we choose as reference case. One good indicator to quantify the level of mass segregation is the ratio of the lagrangian radii of heavy particles to those of light particles, so that values significantly greater than 1 indicate the presence of mass segregation. Of course, the use of lagrangian radii ratios as mass segregation indicators is reliable when the system has a spherical symmetry. Nevertheless, before the first bounce of the system, we observe a fragmentation of the system into various clumps which are not spherical. In such case, a more reliable evaluation of the presence of mass segregation comes

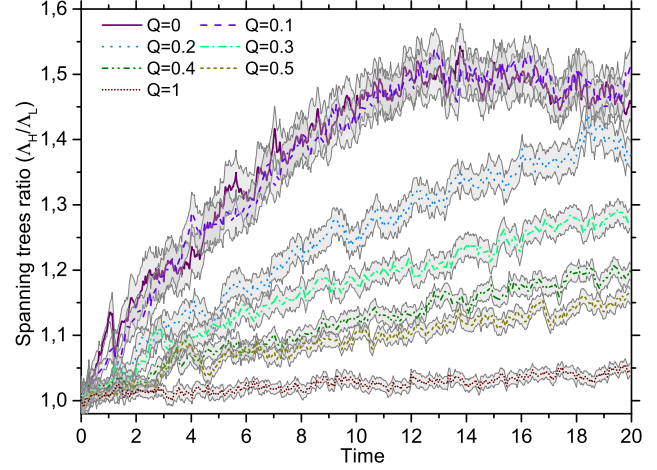


Figure 1. The ratio between Λ_h and Λ_l for several values of the initial virial ratio Q , in Case 1. Values of Q between 0.5 and 0.9 have also been considered, but they are not shown here for the sake of a clear representation of the results. Each curve represents an average value of Λ_h/Λ_l and the error (standard deviation) is represented by the semi-transparent area.

from the so called *minimum spanning tree* method (MST)¹, developed by Allison et al. (2009). Given a sub-set K_m of m points belonging to a system composed of $m' > m$ bodies, the degree of mass segregation established for that sample, Λ_{K_m} , is defined as

$$\Lambda_{K_m} = \frac{\langle l_{norm} \rangle}{l_{K_m}} \pm \frac{\sigma_{norm}}{l_{K_m}} \quad (10)$$

where l_{K_m} is the MST for the sample K_m , $\langle l_{norm} \rangle$ is the average MST for m randomly selected stars in the whole system and σ_{norm} is its associated standard deviation. In each run, we calculate $\langle l_{norm} \rangle$ using 200 different sub-sets of points. From the definition given in Eq. 10 it follows that the generic sample K is mass segregated if Λ_{K_m} is significantly greater than 1.

When we use the MST method to investigate the distribution of masses in our simulations, we need to remove escapers. This removal process is important because, after the first bounce, a significant amount of mass (about 20% of the total mass) is lost; therefore, a single, remote, star may alter significantly the length of the spanning tree of a specific population. To identify escapers correctly, the best criteria are those based upon energy (which should be positive) and distance from the densest region of the system (the core).

3.1 Case 1: systems without gas and without a central black hole

The simplest case we studied concerns systems with neither gas nor a central black hole. To give statistical significance to our results, we generated a set of 30 different initial configurations to evolve, by simply changing the seed of the Mersenne Twister random number generator (Matsumoto & Nishimura (1998)) that provides initial conditions in the phase space. Here we show the results obtained from these simulations.

Fig. 1 shows the ratio between the averaged value of Λ for the heavy (Λ_h) and for the light (Λ_l) stars as a function of time. The first important thing to stress is that the degree of mass segregation

¹ The minimum spanning tree is the shortest path length which connects a certain number of points without forming closed loops.

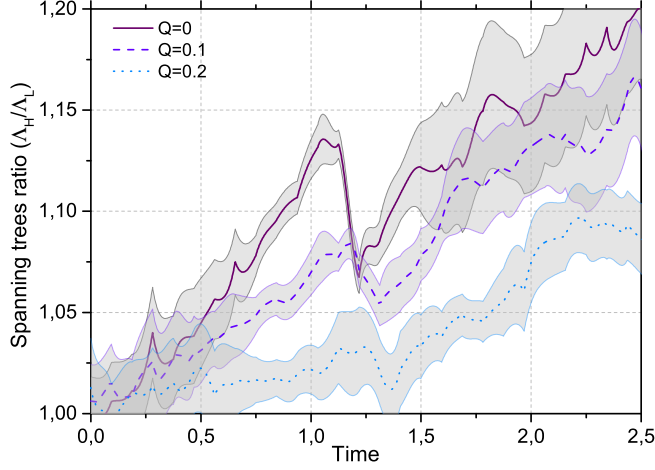


Figure 2. A detail of Fig. 1, zooming in the interval of time between 0 and 2.5.

depends strictly upon the initial state of the system: the farther from equilibrium, the higher and the quicker the degree of the resulting mass segregation on both short and long time scales is. Another important result is that we obtain a significant degree of mass segregation starting from homogeneous and smooth initial conditions. For the cases of most violent collapses ($Q = 0$ and $Q = 0.1$) the system gets to a saturation of the degree of mass segregation around 12 units of time, while, for larger values of the initial virial ratio, the process of mass segregation continues at an approximatively constant rate.

Fig. 2 shows a detail of the Fig.1; in particular, it refers to the initial evolution of the system from $t = 0$ to just after the bounce. This figure makes clear that there is a rapid increase of mass segregation up to $t \simeq 1$; then, an inverse trend is observed for a brief time and, finally, mass segregation starts again with about the same rate and efficiency, as it was before. The series of snapshots in Fig. 3 give a visual sketch of what explained above.

The rapid increase of mass segregation before the bounce is in perfect agreement with the mass segregation observed in the sub-clumps that form during the first system collapse. Nevertheless, when the merging process occurs, the mass segregation is not completely preserved, and Fig.2 shows an inverse trend, indeed. After the merging process, mass segregation continues with the same efficiency as before the bounce but, this time, no sub-structures appear; therefore, mass segregation continues inside the dense core formed just after the bounce. It is thus clear that sub-clumps are not the unique cause of the observed mass segregation on short time scales, and the same can be said for the short-living but very dense core. Actually, both the two phenomena play a role because the first one acts on a very short time-scales, $t \lesssim 1$, while the second one is responsible of the long lived mass segregation for $t \gtrsim t_B$. Times around the collapse phase ($t \simeq t_B$) correspond to a transition between the two regimes. Moreover, this situation is evident for “cool” systems ($Q \lesssim 0.3$); for $Q \gtrsim 0.3$, sub-clumps do not form at all, although a degree of mass segregation significantly greater than that in the equilibrium case ($Q = 1$) is established. In these “warm” cases ($Q \gtrsim 0.3$), the only mechanism active in the rapid and secular mass segregation is the dynamical evolution of the dense core that forms after the collapse.

For completeness, we report in Fig. 4 the results obtained using another indicator of mass segregation, that is the ratio between some lagrangian radii of light and heavy stars. As we said, the ratio

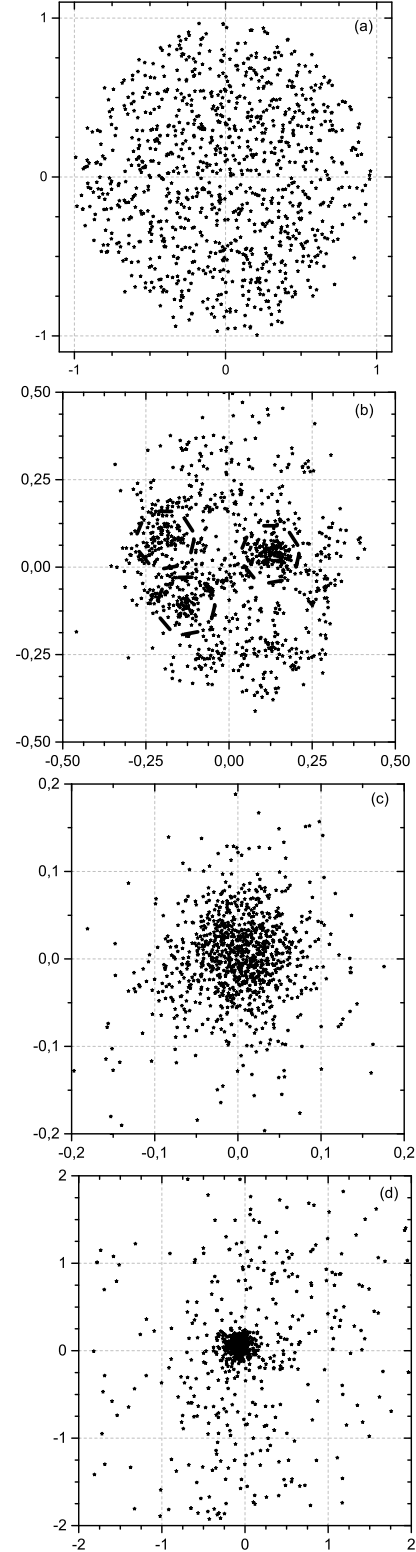


Figure 3. Projection on one coordinate plane (x-y) of one of the simulated clusters with initial virial ratio $Q = 0$ at four different times. Panel (a) shows the homogeneous initial distribution, panel (b) the formation of several sub-clumps ($t \simeq 1$), the most evident of which are circled, panel (c) refers to the state of maximum compression of the stellar system ($t \simeq t_B$), while panel (d) is a view of the cluster after the bounce ($t \simeq 2$).

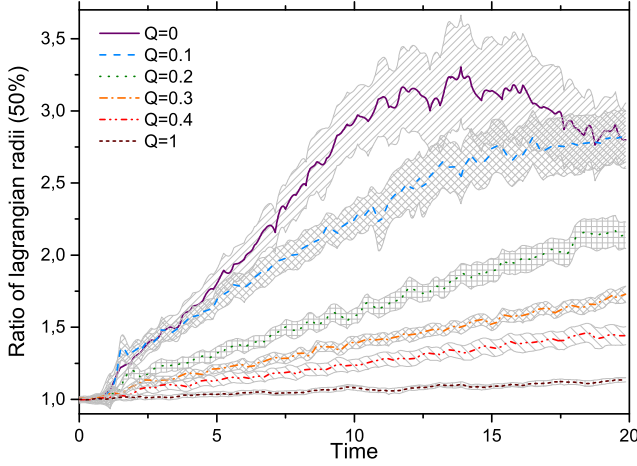


Figure 4. Time evolution of the ratio of the lagrangian radius (that containing 50% of the mass) of light to that of heavy stars in the evolving system, in Case 1. Different curves are for different values of the initial virial ratio Q of the system. The pattern area represents the error associated with each curve.

of lagrangian radii is as better as mass segregation indicator as the studied system maintain spherical symmetry. In our case, this is true at times greater than $\sim t_B$. In other words, we use lagrangian radii to point out the presence of a long lived mass segregation whose efficiency depends on the above described phenomena which occur at $t \lesssim t_B$.

The phenomenon of mass segregation is particularly evident, in Fig. 4, for $Q = 0$. On average, in this case, the typical size of the spatial region occupied by light stars becomes, in 6 crossing times, almost twice larger than the heavy particles one. On the other side, the case $Q = 1$ shows an almost flat behaviour. This confirms again, the strong dependence of the efficiency of mass segregation upon the initial dynamical condition of the system.

3.1.1 Some analytical considerations

It is known (Spitzer 1969) that the segregation time of a sub population of stars of mass M in a system where $\langle m \rangle$ is the average mass is

$$t_{seg}(M) \simeq \frac{\langle m \rangle}{M} t_{rel}. \quad (11)$$

Nevertheless, if the system is far from equilibrium, as it is in our cases, further simplifications of the formula for the relaxation time (see Eq. 2) are not allowed.

An expression which does not assume virial equilibrium, is the following

$$t_{rel} \simeq 0.34 \frac{\sigma^3}{G^2 \langle m \rangle \rho \log \Lambda} \quad (12)$$

while assuming virial equilibrium we get

$$t_{rel} \simeq \frac{N}{8 \log N} \frac{R}{\sigma}. \quad (13)$$

In our simulations, with $N = 1,024$, the dense core contains $N \simeq 350$ stars and has a size $R \simeq 0.15$ pc. The velocity dispersion is $\sigma \simeq 3$ km/s and the average mass $\langle m \rangle \simeq 1 M_\odot$. These values give $t_{rel} = 0.3$ Myr when using Eq. 13, which means that the system evolves fast and can segregate masses, down to $1.5 M_\odot$, on

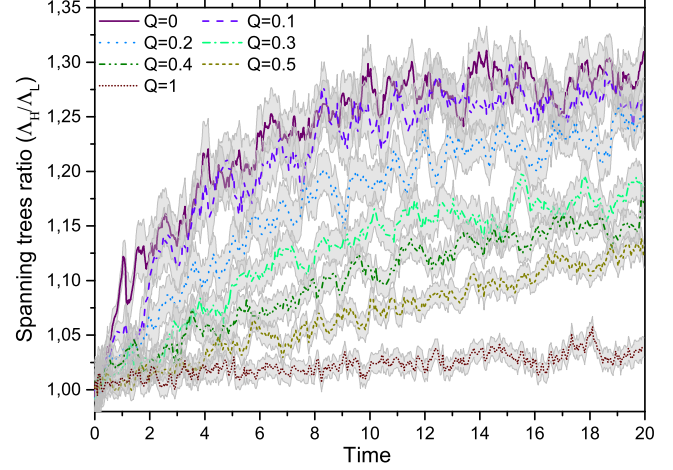


Figure 5. The spanning trees ratio as a function of time, in Case 2. Values of Q label the curves. Values of Q between 0.5 and 1 have been studied, too, but displayed here for the sake of more clear representation of the results. Each curve represents an average value of Λ_h/Λ_l , taking into account the results obtained from the single runs, while the error (standard deviation) is represented by the semi-transparent area.

a very short time scale (the very dense core lives, in our simulations, for about 0.2 Myr). On the other hand, using Eq. 12, we get a value of about 3 Myr for the relaxation time, therefore we have a system that can segregate masses down to $15 M_\odot$ only. This is just one proof of the inconsistency and inapplicability of both formulas 13 and 12 to a situation which is very far from virial equilibrium.

3.2 Case 2: systems containing a central black hole without gas

As we can see in Fig. 5, the presence of a central massive particle, whose mass is 25 times that of a generic “heavy” star, tends to compact the curves of the spanning trees ratios with respect to the case shown in Fig. 1. Actually, the process of mass segregation is less efficient but it is still evident and strongly dependent on the violence of the collapse.

3.3 Case 3: systems containing gas without a central black hole

The majority of young and very young star clusters are still embedded in their proto-cloud. This residual gas, when sufficiently abundant, acts as a background potential which can affect the dynamical evolution of the stellar cluster. In this work we modelled the presence of a gas as an analytical potential to add to the pair gravitational interaction of the bodies in the system. This does not represent very correctly the real astrophysical situation but, using our simple model, we can at least account at order of magnitude accuracy the gaseous phase contribution. The most evident effect of the addition of the analytic gravitational potential is smoothing out the 2-body encounters, decreasing the efficiency of mass segregation on both small and longer time scales.

Figure 6 is the analogous of Fig. 1 with the inclusion of a stationary gaseous background. As we can see, the results for the case of $Q = 0$ are very similar to those obtained for the same case but without the presence of gas; it is still evident the formation of sub-clumps and a quick mass segregation, before the bounce, as

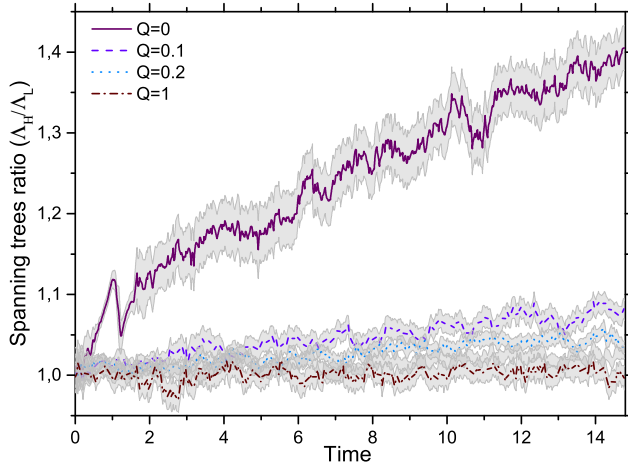


Figure 6. The spanning trees ratio as a function of time, in a case analogous to Case 1 but with a relic, static gas. Values of Q between 0.4 and 0.9, both taken into account in our simulations, are not shown here to have a clearer representation of the results. Each curve represents an average value of Λ_H/Λ_L , taking into account the results obtained from the single runs, while the error (standard deviation) is represented by the semi-transparent area.

much the inverse trend of the spanning trees ratio around the time corresponding to the maximum compression of the system. The mass segregation on a longer time scale is slightly less than that observed for the same value $Q = 0$ in Fig. 1. For values of the initial virial ratio $Q \gtrsim 0.1$ the situation deeply changes. Actually, the presence of gas reduces the role of close encounters between stars and the process of mass segregation is less efficient. Although this point deserves a deeper investigation, it is possible to point out that the case $Q = 0.1$ is profoundly different respect to the case of absence of gas as it is seen also in the evolution of the distribution of the velocities of the stars (Fig. 7).

Figure 7 shows the distribution of the velocities of the stars at different times. In both the cases of presence and of absence of a gas component, the initial velocity distributions follows approximately the same trend. The situation deeply changes after ~ 1 crossing time: the velocity dispersion in the system which does not include gas becomes rapidly broader than the other case. This implies that the background potential reduces the efficiency of the 2-body interactions and, then, reduces the possibility to form gravity-driven substructures (clumps) and the efficiency of mass segregation. At the bounce, the difference between the two systems is even more pronounced and, after ~ 2 crossing times, the two distributions are completely different. In particular, the presence of the gas tends to pack the velocity distribution toward the same, small, velocity. On the other hand, the velocity distribution, when no gas is present, is extended over a huge range of velocities. This is the natural consequence of more efficient 2-body encounters which make the system segregate masses more rapidly.

We have also studied the case of an expanding background gas, represented as a Plummer sphere where the core radius, r_c , is not constant but, rather, evolving according to the law $r_c(t) = r_c(0) \exp(t/\tau)$, where the time scale τ is set equal to the crossing time of the system (t_c) and $r_c(0) = R$. The total amount of the mass in gas is given by the star formation efficiency parameter S (see Eq. 7); we recall that, in our simulations, we have $S = 0.3$. The law is such that the core radius amplify its value of a factor k after a time $t_k = \tau \ln k$. Fig. 8 gives the spanning trees ratio in this

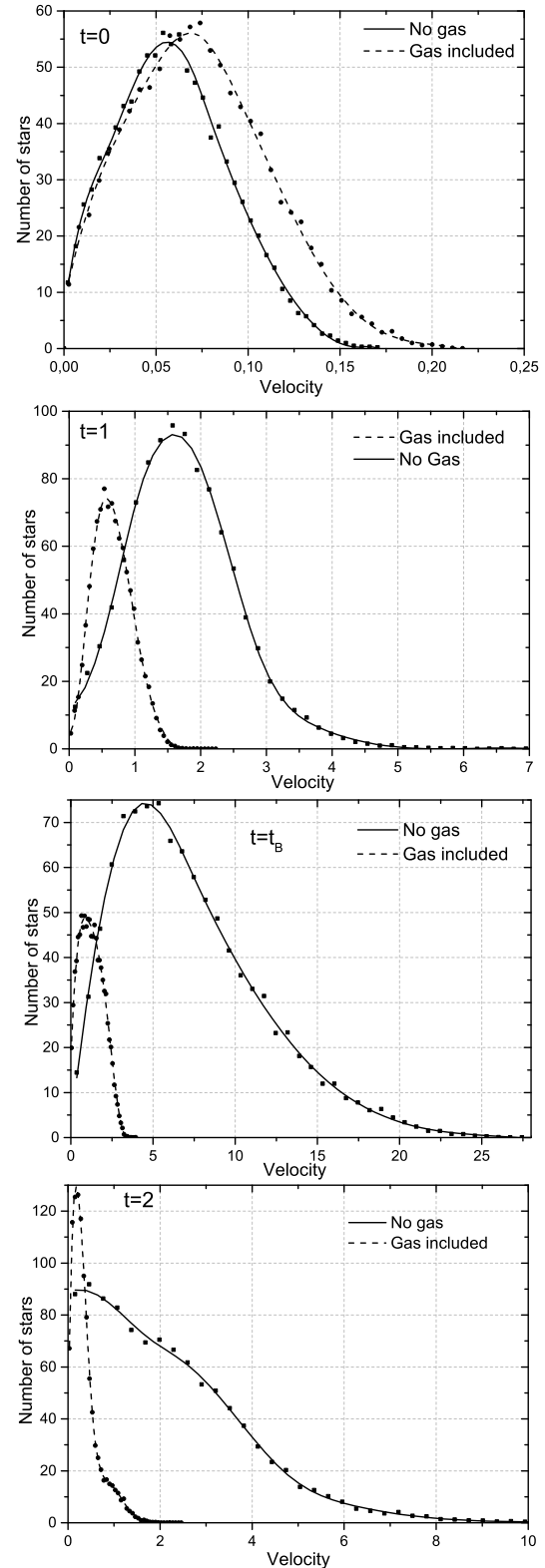


Figure 7. The star velocity distribution in the case of a system without any background gas (Case 1, solid line) and in presence of a background static gas (dashed line). The initial value of Q is 0.1. The four panels represent different times: the initial state, the situation after 1 crossing time, at the time of the bounce and after 2 crossing times.

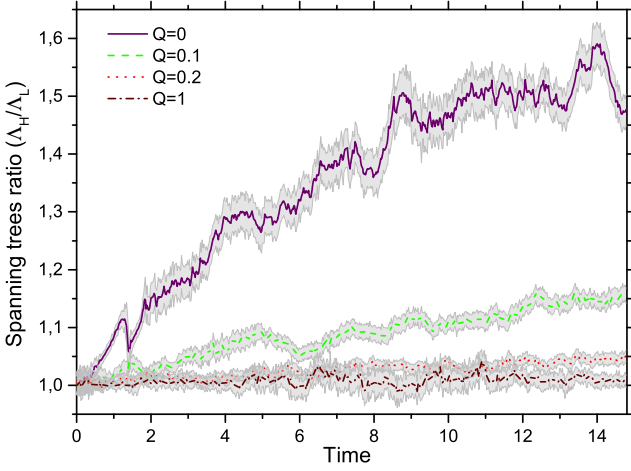


Figure 8. As in Fig. 1 but with the inclusion of a relic gas treated as a smooth gravitational potential in expansion according to a given law. The different values of the initial Q are labelled. Each curve represents an average value of Λ_H/Λ_L , taking into account the results obtained from the single runs, while the error (standard deviation) is represented by the semi-transparent area.

expanding case, for 4 values of the initial virial ratio Q . We note how the spanning trees ratio do not show significant differences from the behaviour they have in the static gas potential case (Fig. 6). In particular, the curves in Fig. 8 reproduce the trends reported in Fig. 6 (the static gas case) for values $0.1 \leq Q \leq 1$. Compared to the static gas case, here the spanning trees ratio are comparatively larger, stabilizing at a value of ~ 1.5 after $\sim 8t_c$, in the zero initial velocities case ($Q = 0$). This means that, also in this case, the violent mass segregation effect is quite evident.

4 DISCUSSION AND CONCLUSIONS

The main scope of this paper was the study of the topic of quick mass segregation in a stellar system composed by a moderate number of stars. The relevance of this topic is suggested by observations showing, unexpectedly, mass segregation in young clusters, often still embedded in the gas left by the gaseous protocloud. Despite some effort, both on the observational and theoretical side, no firm conclusions on the origin of the observed mass segregation at the level observed in young embedded clusters have been drawn on a theoretical and/or numerical side.

To attack this problem properly, and without exceeding in useless details which can mask the main physical processes governing the phenomenon, we considered clusters of moderate size ($128 \leq N \leq 1,024$) as composed by stars with two different masses (m_l and m_h , with $m_h = 2m_l$), spanning a range of initial virial ratios Q between cold conditions, $Q = 0$, through cool, and warm conditions, $Q \leq 1$.

Numerical simulations of the N -body evolutions were performed by mean of the high-precision and high-speed `HiGPUs` code (Capuzzo-Dolcetta et al. 2013). It is worth noting that, although the code, at the moment, does not implement any special treatment to integrate neither binaries nor multiples and to deal accurately with very close encounters, the simulations we performed so far are numerically very precise despite the criticality of the initial conditions of the tested systems (initially null velocities of the stars, corresponding to the most violent collapse). To quantify this,

we show in Fig. 9 the relative variation of the total energy of the system in the case $N = 1,024$, $Q = 0$, without presence of gas but with the presence of the central heavier particle. It is seen in the Figure that the relative variation of energy, $|E(t) - E(0)|/|E(0)|$, is always below 10^{-5} even after the core collapse of the system, that occurs at time $t_{cc} \sim 7t_c$, after which very tight multiple systems of stars form at the center, leading to a deep increase of the total energy of the system. This increase is mainly due to the significant reduction of the time step used in the integration of motion which yields to a deep increase of the number of iterations per time unit, and so a significant increase in the round-off error.

We gave statistical relevance to our results by making the average of a set of sampled initial conditions for any of the input parameters chosen (N , Q , presence or absence of a black hole and of a background gaseous component). Moreover, we quantified the level of mass segregation by the use of the powerful minimum spanning tree method (Allison et al. 2009) coupled to the often used lagrangian radii. We have also taken into account the role of escapers on our results, accurately treating the escapers as those stars having positive individual mechanical energy and far enough from the cluster such to have almost zero probability to be recaptured by the cluster itself.

We found that clusters with cool initial conditions ($Q \lesssim 0.3$) segregate masses, in a way almost independent of N in the range of N studied. This happens in two distinct dynamical phases which both contribute to the mass segregation on short or even very short time scales. They are:

- (i) the formation of substructures (clumps) as the system undergoes its initial collapse, which segregate masses very quickly (this phenomenon acts in the first evolution of the system *before* the bounce of the system while, during the bounce, the clumps are completely removed);
- (ii) the subsequent formation of a very dense core which is responsible for the mass segregation of the system that is clearly evident *after* its bounce when no clumpy structures are formed.

The first phase practically corresponds to the initial gravitational instability of the system and thus is related to the value of the Jeans mass of the system in dependence on the assumed initial virial ratio, in the sense that warmer initial conditions tend to cancel the role of this phase. On the other side, the second phase, although it is stronger in its effects for lower values of Q , remains significant in segregating masses on an extended interval of Q . Both the phases occur on time scales much shorter than the (ill defined, when out of equilibrium) 2-body, gentle relaxation time of the system.

On both the two phases of mass segregation has a relevance the inclusion of a “background” potential which mimics the presence of a residual gas left after star formation as well as the inclusion of an additional body as heavy central object (a stellar black hole). Quite clearly, the role on the cluster dynamics played by the background gas general potential depends on the characteristics of its time evolution (if it is very rapid it may influence both the phases). The cases studied here (static and expanding gas) indicate that the addition of gravitational binding energy tends to smear out the local processes that give mass segregation, although segregation is still clearly visible.

The presence of a black hole ($m_{BH} = 25m_h = 50m_l$) influences just the second phase and the following, secular, evolution of the system. The black hole acts both in reducing the efficiency of close encounters between stars, thus decreasing the rate of energy exchanges and, so, the resulting mass segregation.

To conclude: the results presented here are rough if considered

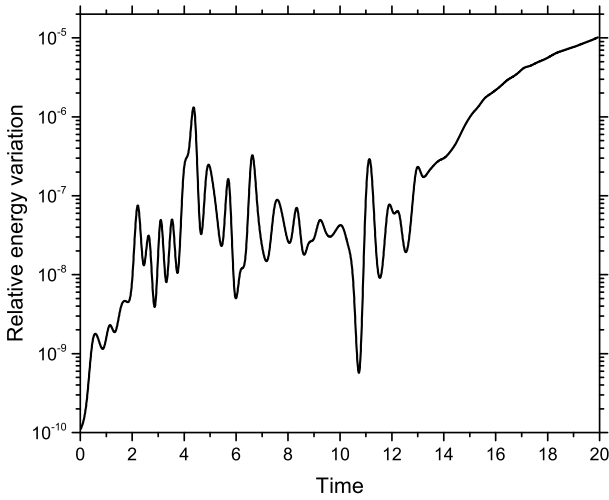


Figure 9. The relative energy variation for the most critical case simulated: $N = 1,024$, $Q = 0$, the inclusion of a central stellar mass black hole and without a gaseous component

on a pure astrophysical side, in what we did not pretend to represent in detail real open clusters, but they are interesting enough on the side of dynamics of small- to intermediate- N -body systems.

Needed future steps to assess more firmly on the modes of violent mass segregation would require a proper inclusion of a primordial binary population, of a realistic mass function, a self consistent treatment of the residual gas and of the gas expelled via stellar winds during stars' evolution. Our future aims include also a very accurate treatment of close encounters between stars, employing a regularization method for the N -body problem. To do this, we will use an updated version of `HiGPUS`, named `HiGPUS-R`, which is still under development.

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